Appendix C
Dimensional Analysis for Groin Design and Example Applications

C-1. Dimensional Analysis.

A dimensional analysis of the variables important in groin design can provide insight into the factors governing the functional design of groins. The variables that describe the behavior of groins are summarized in Figure C-1. For a groin system, the variables and their dimensions (in square brackets) are,

ℓ_u = groin length along the updrift side of the groin (measured from the beach berm), [L]

ℓ_d = groin length along the downdrift side of the groin (measured from the beach berm), [L]

x = distance between adjacent groins (groin spacing), [L]

H_b = breaking wave height in the groin compartment, [L]

d_b = water depth in which waves break, [L]

d = water depth at the seaward end of the groin, [L]

T = wave period, [T]

z = mean tidal range at site, [L]

α_o = original shoreline orientation (measured from some arbitrary alignment), [dimensionless]

α = reoriented shoreline alignment, [dimensionless]

or, in lieu of the above two angles

$\delta\alpha = \alpha_o - \alpha$ = change in shoreline alignment caused by groins, [dimensionless]

Note: $\delta\alpha = \tan^{-1}\left[\frac{\ell_d - \ell_u}{x}\right]$

g = acceleration of gravity, [L]/[T]^2

Q_n = original potential net longshore sand transport rate [L]^3/[T]

Q_{groin} = potential longshore transport rate with groins, [L]^3/[T],

A_s = "wet area" between groins, [L]^2,

Note: $A_s \approx \left[\frac{\ell_d + \ell_u}{2}\right] x$

K_r = reflection coefficient for the groin, [dimensionless]

K_t = transmission coefficient, [dimensionless]

h = groin height above the mean low water (MLW) line, [L]

One possible set of dimensionless variables is given by,

$\pi 1 = \frac{x}{\ell_u}$ = dimensionless groin spacing based on updrift groin length

$\pi 2 = \frac{x}{\ell_d}$ = dimensionless groin spacing based on downdrift groin length

or, $\frac{\ell_u}{\ell_d}$ = shoreline offset across a groin

can be substituted for either of the two preceding dimensionless terms,

$\pi 3 = \frac{H_b}{d}$ = dimensionless breaker height (a measure of where breaking waves occur relative to the groin's end)

$\pi 4 = \frac{d}{d_b}$ = dimensionless water depth at the groin's end at MLW

$\pi 5 = \frac{d}{\ell_u}$ = average beach slope along the updrift side of the groin

or alternatively, $\pi' 5 = \frac{d}{\ell_d}$ = average beach slope along the downdrift side of the groin

$\pi 6 = \delta\alpha = \tan^{-1}\left[\frac{\ell_d - \ell_u}{x}\right]$, shoreline reorientation

$\pi 7 = \frac{H_b}{gT^2}$ = dimensionless breaker height index, (proportional to H/L)

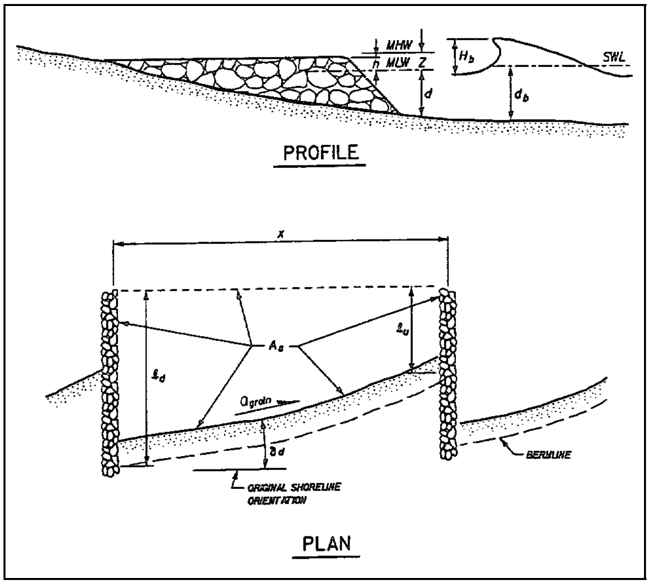


Figure C-1. Definition of terms--dimensional analysis of groins and groin fields (MHW = mean high water; MLW = mean low water; and SWL = still-water level)

$\pi 8 = \frac{A_s}{xd}$ = dimensionless water area between two adjacent groins,

$\pi 9 = \frac{z}{d}$ = dimensionless tidal range (based on at end of groin)

$\pi 10 = \frac{h}{z}$ = dimensionless groin crest height,

Note: If $h/z \geq 1$, then the groin crest is above the MHW line; if $0 \leq h/z \leq 1$, the groin crest is within the mean tidal range, and if $h/z \leq 0$, the groin is submerged at low tide.

$\pi 11 = K_r$ = wave reflection coefficient for the groin

$\pi 12 = K_t$ = wave transmission coefficient for the groin

$\pi 13 = \frac{Q_n}{H_b^{5/2}\, g^{1/2}}$ = a dimensionless measure of the net longshore transport

$\pi 14 = \frac{Q_{groin}}{Q_n}$ = dimensionless net longshore transport reduction attributable to the groins.

a. π1 and π2 are dimensionless groin spacings, one based on groin length as measured along the updrift side of a groin, the other based on length measured along the downdrift side. Rule 7 (refer to Chapter 3) suggests that $\pi 1 \leq 3$ and $\pi 2 \geq 2$.

b. π3 determines whether waves normally break seaward or landward of the groin's end. If $\pi 3 \geq$ about 0.78, waves will generally break seaward of the groin's end, and sand will bypass the groin even during normal wave conditions. If $\pi 3 \leq$ about 0.78, waves will normally break landward of the groin's seaward end. The magnitude of π3 determines whether a groin is "long" or "short." Similarly, π4 determines whether waves break seaward or landward of the groin's end.

c. The average beach profile slope along the updrift side of the groin is indicated by π5.

d. π6 is a measure of the reorientation of the shoreline between two adjacent groins in a groin system or a measure of the shoreline discontinuity between the two sides of a groin.

e. π7 is an indicator of the wave environment at the site. The assumption here is that the wave environment can be described by a single "characteristic wave." The "characteristic wave" is one that best describes longshore sand transport conditions at the site. The mean wave height and mean wave period at a site might be used as the "characteristic wave."

f. π8 is a measure of that area between two adjacent groins in a groin system that will not fill with sand or will not retain sand. It is a measure of how much sand will be removed from the groin system before the shoreline reaches a quasi-steady equilibrium configuration. If the shoreline between two groins is assumed to be straight, π8 is related to π1, π2 ,and π5 approximately by $\pi 8 = \frac{1}{2}\pi 1 (\pi 1 + \pi 2)/\pi 5$.

g. The dimensionless tidal range is given by π9. It is a measure of how much the water depth at the end of the groin changes over a tidal cycle.

h. The height above the groin crest above the MLW (or mean lower low water) line is given by π10. If $\pi 10 \geq 1$, then the groin crest is always above the water level except possibly during storm surges. If $0 < \pi 10 < 1$, the water level is alternatively above and below the groin's crest depending on the stage of the tide. For $\pi 10 \leq 0$, the groin is submerged even at low tide.

i. π11 and π12 are the wave reflection and wave transmission coefficients of the groin. They are probably of lesser importance to the successful function of groin systems than are the other dimensionless variables.

j. π13 and π14 are measures of the longshore transport environment at the groin site. π13 is a measure of the potential net transport and, indirectly, a measure of a characteristic longshore transport wave angle. π14 is a measure of the reduction in longshore transport brought about by the construction of groins. It is indirectly a measure of how much the shoreline is reoriented--and how much sand transport is reduced--by the groins.

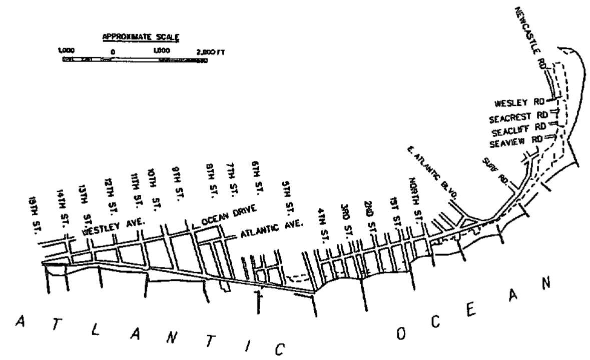
C-2. Example Applications.

Many of these dimensionless variables can be determined from an analysis of nearby groins and transposed to the site of a proposed groin project. Analysis of aerial photographs and field measurements can be used to determine reasonable values for the above variables. They can then be used to functionally design a groin system. Even data taken from groin projects deemed to be unsuccessful can be examined in light of the foregoing dimensionless terms and modified to develop a successful design. Application of the dimensionless parameters to a groin design is illustrated in Example 1.

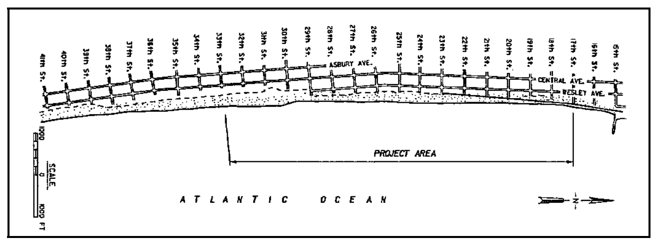
a. Example 1

(1) Problem: (The example that follows is entirely hypothetical and not intended to be an actual design.) A beach fill is planned for an 18-block-long area of Ocean City, NJ, from 17th Street in the north to 33rd Street in the south. See Figures C-2a, b, and c for a location map. A minimum beach berm width of 100 feet[*] measured seaward from the existing bulkhead line is desired. Groins are to be evaluated as a means of stabilizing the beach and retaining the fill within the project area. Because of the developed nature of the shoreline, the potential for erosion along both updrift and downdrift beaches is a concern. Some of the fill is expected to leave the project area to nourish adjacent beaches.

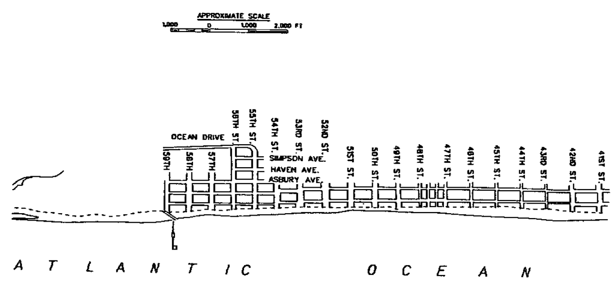
(2) Groins have been built along adjacent beaches to stabilize them. North of about 15th Street, groins are located about 1,000 feet apart along the shoreline. Also, there is a "terminal" groin at the south end of the developed portion of the island at 54th Street. Analysis of aerial photographs taken of these other groins indicates that the shoreline alignment varies from an average azimuth of about 37 degrees to about 70 degrees.



a. Northern section of Peck Beach Project area



b. Center section of Peck Beach Project area



c. Southern section of Peck Beach Project area

Figure C-2. Location map for Example 1, Ocean City, NJ, shoreline

Table C-1 gives the shoreline azimuth taken from three sets of aerial photographs for both high and low tide shorelines within the various groin compartments. Along the northerly Ocean City beaches, the shoreline alignment in the groin compartments reflects the variation in potential longshore transport rates and directions caused by the proximity of Great Egg Harbor Inlet and its offshore shoals. The net longshore sediment transport is southward along most of Ocean City's shoreline; however, along the northernmost beaches, due to sheltering of the beaches from waves out of the northeast by the shoals offshore of Great Egg Harbor Inlet, the net transport is

[*] To convert feet into meters, multiply by 0.3048

Table C-1
Shoreline Orientation at Various Locations in Ocean City, NJ

Location	Shoreline Orientation*					Average
	25 October 1965		30 March 1984	8 August 1984		
	HWL**	LWL	LWL	HWL	LWL	
34th Street	55.50	55.05		55.50	55.50	55.50
25th Street				58.50	58.50	58.50
15th Street						
13th Street	63.50	62.50	63.00	64.50	69.00	64.40
11th Street	64.25	62.00	73.50	74.00	71.00	68.95
9th Street	58.25	73.50	71.00	72.50	75.00	70.05
7th Street		60.00		76.00	70.00	68.67
5th Street	48.00	65.50		65.00	64.00	63.13
3rd Street	60.75	62.00	60.00	61.50	76.50	64.15
1st Street	56.50	64.00		50.00	52.00	53.63
North Street	60.50	61.00	59.50	63.00	64.00	61.60
Groin E	54.50	59.50	44.00	59.00	60.00	55.40
Groin D	46.50	51.00	41.00	43.00	43.00	44.90
Groin C	40.00	47.00	30.00	34.50	32.50	36.80
Groin B	39.50	45.00	34.00	42.50	43.00	40.80
Groin A						

* Angle measured clockwise from north.
** HWL = high-water level; LWL = low-water level.

northward--toward the inlet. Thus, waves from the southeast can move sand northward whereas waves from the northeast have their sand-moving capability reduced by the inlet's ebb-tidal shoal. The result is a northward net transport along the beaches close to the inlet. Thus, the groins near the inlet are not illustrative of groins that might be built farther south.

(3) The results of an analysis of groin length taken from two sets of aerial photographs dated 25 October 1965 and 8 August 1984 are given in Table C-2. (Under actual design practice, additional sets of more recent aerial photographs that might show seasonal shoreline fluctuations would be analyzed.) The length of the groin measured from the seaward end to the high- and low-water lines along both the updrift and downdrift sides is given in Table C-2. Average values are also given. The variability in length is apparent in the tabulated values. In fact, the groins closest to the project site are those at 15th, 13th, and 11th Streets, and average values for these groins were analyzed to determine groin dimensions. Based on this analysis, the average distance from the seaward end of the groin to the low-water line along its updrift side is 208 feet; the distance to the low-water line along its downdrift side is 289 feet. The distance from the end of the groin to the high-water line along its updrift side is 396 feet, and the distance along its downdrift side is 475 feet.

(4) Typical beach profiles taken at 27th and 36th Streets are shown in Figures C-3 and C-4, respectively. Based on an average groin length of 650 feet measuredfrom the bermline, the seaward end of the groin terminates in either 4 or 6 feet of water based on these profiles. Note that these profiles are located some distance from the existing groins. In actual practice, beach profiles taken adjacent to the groins should be obtained, and the water depth at the seaward end of the groins determined. For the present example, the water depth at the end of the groin will be assumed to be 5 feet. The MLW and (MHW) lines are also shown on the profiles. The average beach slope across the intertidal zone is about 0.021.

(5) Wave conditions at Ocean City, NJ, were obtained from the Wave Information Study (WIS) hindcasts (Jensen 1983[*]) and compared with data presented in Table 4-4 in the *Shore Protection Manual* (SPM) (1984). Weighted average wave heights and periods were determined from the WIS hindcasts at Station 62 (Peck Beach, NJ). The weight factor was the duration that waves of a given height class or period class prevailed. Based on this analysis, the average wave height at Ocean City is 2.1 feet, and the average wave period is 6.5 seconds. The WIS wave height is in water 10 meters (32.8 feet) deep. A linear shoaling analysis to determine the breaking height of the average wave yields a breaker height of 3.0 feet. (The nearshore breaking criterion used was a ratio of wave height to water depth of 0.78.) The corresponding water depth in which the average wave breaks is thus 3.9 feet. Table 4-4 of the SPM gives an average breaking wave height of 2.8 feet at Atlantic City just north of Ocean City, and a period of 8.3 seconds. Wave heights of 2.4 and 1.8 feet and periods of 6.1 and 6.6 seconds are given for Brigantine, NJ, and Ludlam Island, NJ, respectively. These values are based on visual observations. Thus, the values determined from the WIS data and SPM (visual observation data) are in approximate agreement.

[*] See References at the end of the main text.

(6) The water area enclosed within the compartment formed between two groins was determined by planimetering the aerial photographs. Specifically, the compartments between the 15th and 13th Street groins and between the 13th and 11th Street groins were investigated. The areas seaward of the mean low-water line and seaward of the high-water line were determined. The values are given in Table C-3.

(7) The dimensionless variables describing the groins and groin compartments can be determined from the above variables. Note that some of the variables can be defined either for the individual groins or for the compartment formed by an updrift groin and a downdrift groin. For example, ℓ_u and ℓ_d can be defined as the distances on the opposite side of a single groin, or they can be defined as the distance measured along the updrift groin and downdrift groin at opposite ends of a groin compartment. Therefore, $\pi 1$ and $\pi 2$ are defined only for groin compartments while ℓ_u/ℓ_d can be defined either for a single groin or for a groin compartment. $\pi 1 = x/\ell_u = 1178/412.5 = 2.85$ where the distance is measured from the high-water line in the 15th-13th Street groin compartment rather than the beach berm. If the distance is measured from the low water line in the 15th-13th Street groin compartment, $\pi 1 = 4.60$. Similar analysis of the 13th to 11th Street groin compartment yields $\pi 1 = 2.43$ for the high-water line and $\pi 1 = 5.22$ for the low-water line. $\pi 3 = H/d = 3.0/5.0 = 0.6$. Since $\pi 3 < 0.78$ waves normally break seaward of the groin's end at low tide. Similarly, $\pi 4 = d/d_b = 5.0/3.9 = 1.28$. Since $\pi 4 > 1.0$, the depth at the end of the groin is shallower than the

Table C-2
Distance from Seaward End of Groins to the High-Water and Low-Water Shorelines at Ocean City, NJ, Aerial Photograph Analysis

		Groin Analysis - Ocean City, NJ							
		25 October 1965				8 August 1984			
Groin	Spacing	Length HWL, ft (Updrift)	Length HWL, ft (Down)	Length LWL, ft (Updrift)	Length LWL, ft (Down)	Length HWL, ft (Updrift)	Length HWL, ft (Down)	Length LWL, ft (Updrift)	Length LWL, ft (Down)
15th Street		465.00	504.00	323.00	387.00	360.00	480.00	280.00	340.00
	1176								
13th Street		426.00	504.00	118.00	194.00	340.00	420.00	240.00	240.00
	930								
11th Street		465.00	527.00	139.00	295.00	320.00	440.00	240.00	280.00
	1451								
9th Street		310.00	543.00	124.00	465.00	200.00	420.00	100.00	300.00
	1002								
7th Street		543.00	543.00	310.00	310.00	400.00	440.00	340.00	380.00
	1198								
5th Street		349.00	713.00	194.00	464.00			380.00	380.00
	1116								
3rd Street		658.00	658.00	349.00	388.00	600.00	600.00	440.00	440.00
	1063								
1st Street		426.00	589.00	194.00	348.00	360.00	5440.00	200.00	480.00
	534								
North Street		201.00	233.00	0	0	200.00	200.00	128.00	160.00
	690								
Groin E		349.00	504.00	78.00	271.00	280.00	340.00	280.00	260.00
	819								
Groin D		310.00	310.00	82.00	78.00	200.00	220.00	160.00	160.00
	765								
Groin C		116.00	310.00	39.00	116.00	120.00	240.00	80.00	200.00
	679								
Groin B		78.00	232.00	0	465.00	80.00	208.00	60.00	140.00
	806								
Groin A		78.00	310.00	0	387.00	80.00	520.00	60.00	380.00
AVERAGE		341.00	462.88	131.21	297.79	270.77	388.31	212.00	295.71
STD DEV		174.78	155.62	112.85	149.91	149.13	134.87	121.27	108.47

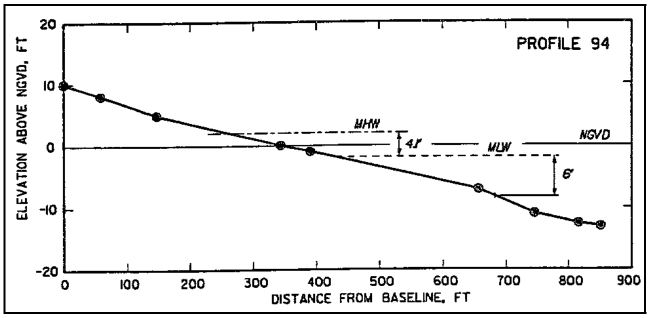


Figure C-3. Beach profile at 27th Street, Ocean City, NJ (elevation (el) measured in feet, National Geodetic Vertical Datum (NGVD)

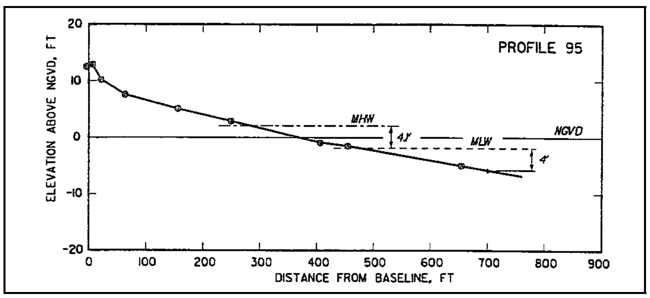


Figure C-4. Beach profile at 36th Street, Ocean City, NJ

Table C-3. Water Area Enclosed Between Groins Seaward of High and Low Water Lines

G roin Compartment	Water Line	Area (sq ft)*
15th - 13th Street	HWL	515,100
15th - 13th Street	LWL	278,600
13th - 11th Street	HWL	402,700
13th - 11th Street	LWL	216,200

* To convert square feet into square meters, multiply by 0.0929.

breaking depth at low tide. $\pi 5 = d/lu = 5.0/400 = 0.0125$, which is the average beach slope between the groin's seaward end and the high-water line along the groins updrift side, or $\pi 5 = d/l_u = 5.0/225 = 0.0222$, which is the average slope between the groin's end and the low-water line along the updrift side. Similar calculations could be made for the downdrift side of the groin. (Note these calculations are averages for the two compartments formed by the 15th and 13th Street groins and by the 13th and 11th Street groins.) $\pi 6$ cannot be determined in the present analysis since the original shoreline orientation prior to groin construction is not known so the change in orientation brought about by groin construction cannot be determined. $\pi 7 = H/gT^2 = 3/(32.17)(6.5)^2 = 0.0022$. $\pi 8 = A_s/x_d = 515{,}100/(1178 \times 5) = 87.4$ based on the MHW value of A_s and $\pi 8 = 47.3$ based on the MLW value of As. These values are for the 15th-13th Street groin compartment. $\pi 8 = 86.6$ and 46.5 for the MHW and MLW values respectively, for the 13th-11th Street groin compartment. $\pi 9 = z/d = 4.1/5 = 0.82$, the dimensionless tidal range. The existing groin crests at 15th, 13th, and 11th Streets are well above the MHW line. If the proposed groins are to be built to a crest height of MHW at their seaward end, the value of $\pi 10 = h/z$ will be $4.1/4.1 = 1.0$.

(8) Potential longshore sand transport rates at Peck Beach (Ocean City, NJ) were computed using WIS hindcast data (Jensen 1983). The analysis resulted in an annual net longshore transport rate of about 73,000 cubic yards[**]/year or 0.062 cubic feet[†]/second and a gross transport rate of 1,485,000 cubic yards/year or 1.271 cubic feet/second. Therefore, $\pi 13 = 0.00070$. Since the reorientation of the shoreline cannot be estimated, the change in longshore transport and thus $\pi 14$ cannot be calculated. However, the ratio of net transport to gross transport is 0.062/1.270 = 0.049. The net transport represents only about 5 percent of the gross transport.

(9) Using the results of the dimensional analysis and the analysis of conditions within the two groin compartments between 15th and 13th Streets and between 13th and 11th Streets, the conditions that can be expected to prevail at the project area can be determined. The groin length and expected shoreline reorientation are shown in Figure C-5. The seaward end of the groins should be about 670 feet from the desired bermline. The high-water line along the downdrift side of the updrift groin will be about 475 feet from the end of the groin while the low-water line will be about 290 feet from the end of the groin. The resulting beach slope between the high- and low-water lines will be 4.1/(475-290) = 0.022, which is close to the values on the existing profiles shown in Figures C-3 and C-4. The high-water line along the updrift side of the downdrift groin will be about 396 feet from the groin's seaward end while the low-water line will be about 208 feet. The beach slope between the

** To convert cubic yards to cubic meters, multiply by 0.7646).

† To convert cubic feet to cubic meters, multiply by 0.0283.

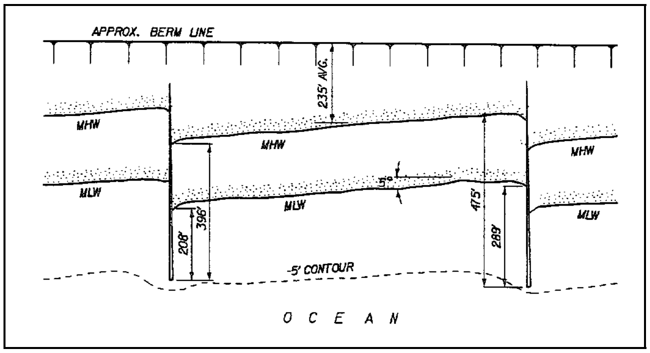


Figure C-5. Expected location of high-water and low-water shorelines after the construction of groins at Ocean City, NJ

high- and low-water lines will be 4.1/(396-208) = 0.022, or the same as along the downdrift side. The groin profile and updrift and downdrift beach profiles are shown in Figure C-6. The sloping portion of the groin has a slope of 0.022 to act as a template for the updrift beach profile. Both the updrift and downdrift profiles meet at the seaward end of the groin at about the -5-foot contour. The berm height is estimated to be at about +8 feet above mean sea level. (The approximate elevation above which dune vegetation can be established in Ocean City is about +7.5 feet.)

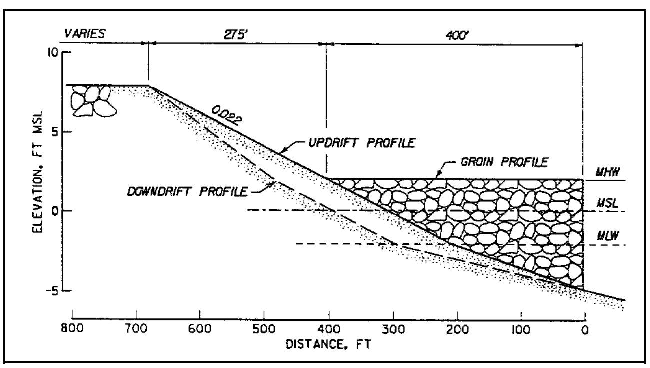


Figure C-6. Groin profile and expected beach profiles after the construction of groins at Ocean City, NJ

(10) The existing groins in Ocean City are spaced about 1,000 feet apart (Table C-2). This spacing was no doubt dictated by the spacing of the streets in Ocean Citywith the groins positioned at the ends of the odd numbered streets. Calculations of the ratio of the groin spacing to the groin length as measured from the berm line give x/l = 1,000/670 = 1.49. Also, the groin dimensions determined from the analysis give a shoreline reorientation of about 5 degrees.

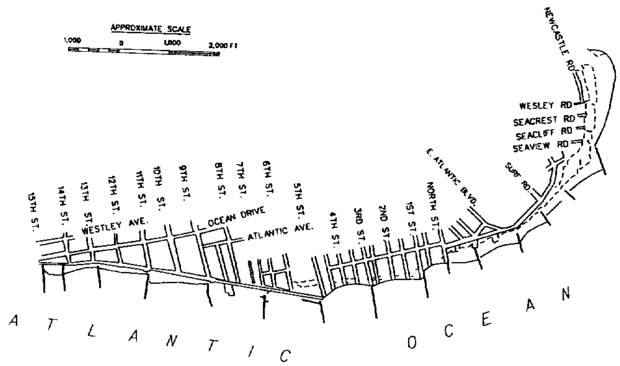
(11) Comparing the values of shoreline alignments in Table C-1, there is about a 6 degree difference in orientation between the shoreline at 25th Street and the alignment in the 15th-13th Street groin compartment. The computed values are therefore reasonable. At this point in the design, a detailed evaluation of the preliminary design might be undertaken using GENESIS (Hanson and Kraus 1989) to compute the shoreline response to a wave climate typical of Ocean City. Refinements in groin length and spacing would result.

(12) Because of the shoreline development both updrift and downdrift of the proposed project, transition sections with groins of decreasing length should be considered. Equations 3-1 and 3-2 in the main text establish the length of the groins in the transition section and their spacing. The ratio of groin spacing to length in the groin field is about 1.5; thus Equation 3-1 gives L = 0.48 L.

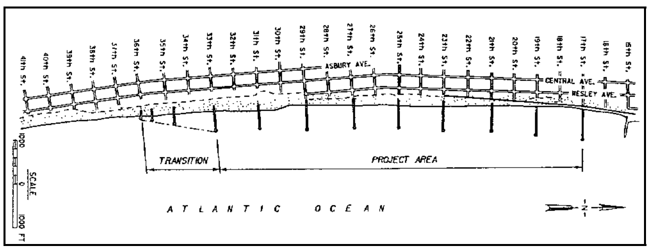
(13) Therefore, in the downdrift transition, each successive groin will be about half the length of the one updrift of it. The first groin in the transition section will be 0.48(670) = 322 feet long as measured from the desired bermline. The third will be 154 feet long, etc. The spacing given by Equation 3-2 yields S = 1.39 L. Therefore, the first groin in the downdrift transition section will be located 1.39(670) = 930 feet downdrift of the project groin field. The second will be 1.39(0.48 × 670) = 450 feet downdrift, and the third, 215 feet downdrift. The groin field and transition sections are shown in Figures C-7a, b, and c.

b. Example 2

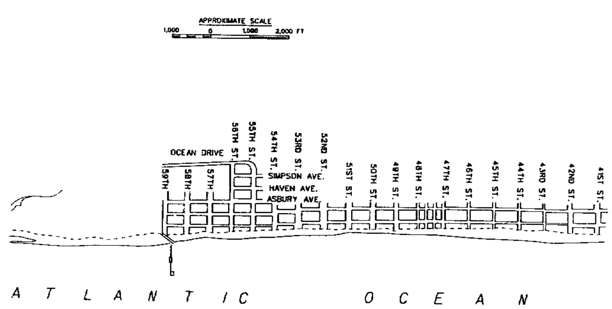
(1) The following example application of a groin design was taken from the General Design Memorandum (GDM) for a shore protection project in Manatee County Florida (US Army Engineer District (USAED), Jacksonville 1990). The authorized project consists of restoration of 3.2 miles (5.15 kilometers) of gulf shoreline on Anna Maria Key to an elevation of 6 feet above MLW, with a 50-foot berm width and natural slopes seaward as would be shaped by wave action. In addition to the initial fill, the authorized project also provided for future nourishment of the restored beach and adjacent shorelines as needed. One of the alternatives considered in the GDM was the use of groins to hold the project design cross section in front of two designated locations of shoreline. Otherwise, higher nourishment quantities would be required due to significant losses of material from these two areas.



a. Northern end of Ocean City, NJ



b. Central section of Ocean City, NJ



c. Southern end of Ocean City, NJ

Figure C-7. Location of groins and groin transition sections

(2) The following is an excerpt of the groin design section included in the Appendix of the GDM (USAED, Jacksonville 1990). It is included to show a summary of the design process that may be used in a groin project. Also included in the same appendix are summaries of the coastal parameters and natural forces such as winds, waves, currents, storm history, and shoreline change history.

c. Effects of groins on adjacent shoreline. Once the location of the two groins was determined, the next step in the design was to determine the length of the structures and the associated effective updrift and downdrift distances. Based on the performance of the pier at the Manatee County public beach and Groin No. 1 on Treasure Island (Pinellas County, Florida), the groins for this project will have an effective length of roughly 1,400 feet to the north and 600 feet to the south of each structure. The length of each groin for the various berm widths are shown below:

Groin No. 1 length, ft	Groin No. 2 length, ft	Plan Berm width, ft
195	205	Nourishment only
220	230	25
245	255	50
270	280	75
295	305	100

Details of groin's design are developed in the following paragraphs.

d. Design wave.

(1) Table C-4 shows the relationships between H_o/gT^2, H_b/H_o' , and d_b/H_b for a slope of m = 0.037. Figure 2-72, page 2-131 of the SPM (1984) defines the relationships between these variables. Hindcast deepwater waves from Gulf Station 40 (Hubertz and Brooks 1989) of 8.5 feet (5-year), 9.7 feet (10-year), and 10.4 feet (20-year) were used to compute a range of breaking waves, H_b. Wave periods ranging from 4 to 8 seconds were used. The still-water depth at the toe of the rubble groins was reviewed to determine if sufficient water depth existed at the toe of the structure to support the computed breaking wave. Table C-5 displays the data for depth at both the toe and crest of the groins.

(a) Review of the data in Tables C-4 and C-5 suggests that deepwater significant waves will break seaward of the structure. Therefore, the design wave will be depth limited. The nearshore slope seaward of the structure is m = 0.037 (1:27). It is assumed that the design wave for the stability of the quarry stone groin is the maximum wave that breaks directly on the structure. Since the elevation of the groins at the structure toe is +1.1 NGVD, the toe of the groins would not be subjected to breaking wave conditions. The portions of the groin towards the shore would be higher than the seaward portion. The landward groins sections would be the only

Table C-4
Breaking Wave Computations

Wave Period (sec)	for H_o' = 8.5, ft*				for H_o' = 9.7, ft				for H_o' = 10.4, ft			
	H_o'/gT^2	H_b*/H_o'	H_b ft	** d_b ft	H_o'/gT^2	H_b/H_o'	H_b ft	d_b ft	H_o'/gT^2	H_b/H_o'	H_b ft	d_b ft
4.0	0.0165	1.48	12.6	16.1	0.0188	1.60	15.5	19.9	0.0202	1.64	17.1	21.8
6.0	0.0073	1.16	9.9	12.7	0.0084	1.18	11.4	14.7	0.0090	1.20	12.4	16.0
8.0	0.0041	1.08	9.2	11.8	0.0047	1.10	10.7	13.7	0.0050	1.11	11.5	14.8

* The values in this column are interpolated from Figure 2-73 of the SPM (1984).
** The values in this column are determined from the following relationship: depth of breaking is equal to 1.28 times the breaking wave (SPM 1984).

Table C-5
Total Water Depth at Structure Toe

Parameter	Return Period	Water Depth at Toe ft, NGVD	MHW Elevation ft, NGVD	Surge ft		Total Depth ft
Depth at toe	5	5.1	1.1*	3.7	=	8.8
(Depth at structure crest)		(1.2)	(1.1)*	(3.7)		(4.9)
Depth at toe	10	5.1	1.1*	4.9	=	10.0
(Depth at structure crest)		(1.2)	(1.1)*	(4.9)		(6.1)
Depth at toe	20	5.1	1.1*	6.2	=	11.3
(Depth at structure crest)		(1.2)	(1.1)*	(6.2)		(7.4)

* This value is already included in the surge water elevation. It is shown for information only.

sections that would have to resist the design breaking waves. Table C-5 shows the maximum water depth that could be expected at the crest elevation of the groins.

(b) Using Figure 7-4 of the SPM (1984), the maximum waves that break on the structure crest with d_s = 6.1 feet, nearshore slopes of 1:27, and wave periods from 4 to 1 seconds were determined as shown below.

gT^2 (sec)	d_s/gT^2	H_b/d_s	H_b (ft)
4	0.0118	0.95	5.80
6	0.0053	1.00	6.10
8	0.0030	1.05	6.41 (check)
10	0.0019	1.10	6.70 (check)
12	0.0013	1.12	6.80 (check)

(2) The check is to determine what effect underestimating the wave period will have on the breaker height. Based on a summary of deepwater wave hindcast data for all directions (Hubertz and Brooks 1989), waves occur 55.6 hours/year with periods greater than 6.5 seconds, or 6.3 percent of the time. Therefore, a breaking wave with wave periods between 4 to 6 seconds has been selected as the design wave. The design of the groins is based on a 6-foot broken wave acting on the shoreward portions of the groins.

e. Rock structure design.

(1) Rock structures. Two uniform-stone rock structures have been designed to hold the design beach-fill section in the southern end of the 4.2-mile-kilometer project area. Without the groins, the design fill would experience excessive losses of sand. Therefore, the

structures must be designed to be impervious to littoral material up to the design elevation of the beach fill, which is +5.0 feet (NGVD). The elevation of each structure varies along its length, as shown on Figure C-8. To make the groins impervious to sand, the groins will be constructed with a prestressed concrete sheet-pile core. Reinforced concrete or steel sheet piling may be substituted for the core of the groin, depending upon the results of the geotechnical subsurface investigations at the site. These investigations will be conducted during preparation of plans and specifications. The groins will be constructed with armor stone placed on both sides of the concrete sheet pile. The armor stone will protect the concrete sheet pile from wave attack. The armor stone will be placed on a foundation of bedding stone and filter cloth. Figure C-8 shows groin profile and cross-section details.

(2) Weight and slope of armor stone. The median weight and slope of the armor stone for the groin structures are designed in accordance with the SPM (1984). The median weight of the armor stone W_{50} of the groin structure is determined by Equation 7-116 of the SPM (1984):

$$W = \frac{w_r H^3}{K_d (S_r - 1)^3 \cot \theta}$$

where

W_r = 165 pounds/cubic foot* (unit weight of armor stone)

H = 6.0 feet (design wave at structure head)

K_d = 1.6 (stability coefficient from Table 7-8, page 7-206 (SPM 1984), for breaking wave condition and two random layers of rough angular quarry stone at structure head)

S_r = w_r/w_w = 165/64 = 2.58 (specific gravity of armor unit)

w_w = 64.0 pounds/cubic foot (unit weight of water at the site)

cot Θ =2.0 (slope 1:2.0, angle of rock structure slope)

Substituting into the above equation yields an armor stone weight for the structure of 2,830 pounds** or 1.42 tons†.

The range of armor stone weights for the cover layer of two quarry stones of the structure could vary from 0.75W to 1.25W (2,120 to 3,540 pounds) with about 50 percent of the individual stones weighing more than (2,830 pounds). A cross-sectional side slope of one vertical to two horizontal was selected.

(3) Armor layer crest thickness. The top width of the armor stone on both sides of the concrete sheet pile is a minimum thickness of two armor stones. The average thickness of armor stone layer r of the structure on each side of the concrete sheet pile is determined by Equation 7-121 (SPM 1984) as follows:

$$r = n\, k_{\Delta} \left(\frac{W}{w_r} \right)^{1/3}$$

where

n = 2 (layers of armor units)

k_{Δ} = 1.00 (layer coefficient from Table 7-13 (SPM 1984)

w_r = 165 pounds/cubic feet

W = 2,830 pounds

Substituting into the equation yields r = 5.16 feet. The rock structure would be constructed on a filter layer of cloth material. A layer of bedding stone would be placed on the filter cloth. The filter cloth and bedding stone act as a foundation for the armor stone. The bedding stone has a gradation of 1 to 50 pounds.

f. Foundation conditions.

(1) Groin No. 1. This groin is underlain by sand and silty sand, with no bedrock encountered to elevation -34.0 feet, MLW. Five feet of slightly cemented beach rock occur at elevations -2.1 to -7.1, but this layer has blow counts only slightly higher than the surrounding sand, with N values ranging from 9 to 17. This layer will not cause a problem driving the prestressed concrete sheet piles called for in the design.

(2) Groin No. 2. This groin is underlain by sand, with no bedrock encountered to elevation -35.6 feet, MLW.

(3) Both groins have riprap strewn over the nearshore surface resulting from existing groins and revetments in various states of disrepair. The core boring at Groins No. 2 encountered a piece of this riprap at elevation

* To convert pounds (mass) per cubic foot into kilograms per cubic meter, multiply by 16.01846.
** To convert pounds (mass) into kilograms, multiply by 0.4536.
† To convert tons (2,000 pounds, mass) into kilograms, multiply by 907.1847.

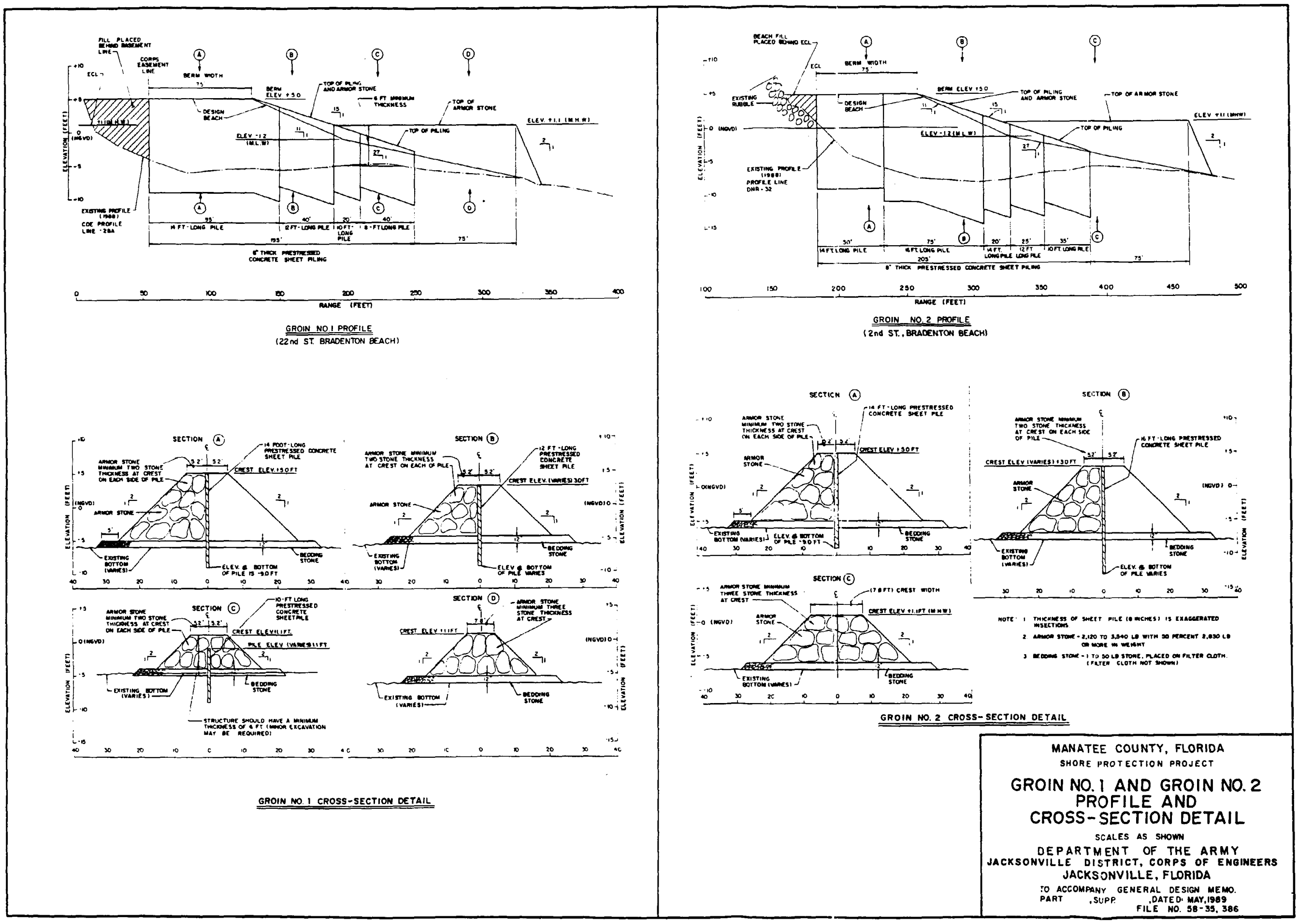


Figure C-8. Groin No. 1 and Groin No. 2 profile and cross-section detail, Manatee County, FL (USAED, Jacksonville 1990)

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-10.0 MLW, and it is safe to assume that scattered riprap occurs throughout the sand column.

g. Predicting future maintenance. Using Table 7-9, page 7-211 of the SPM (1984), the damage that can be expected if the design wave is exceeded can be determined. The future maintenance of the groins can then be estimated. The groins have been designed to withstand a 10-year storm significant wave event with less than 5-percent damage. A maintenance interval of 10 years has been selected. There is a 40-percent probability that a 20-year surge event will occur in a 10-year period. This surge would result in a design depth at the crest of the structure crest of 7.4 feet. Using a wave period of 8 seconds and Figure 7-4 of the SPM, d_s/gt^2 = 0.0036, and H_b/d_s = 1.05. Therefore, H_b = 7.8 feet, and H/H_D = 7.8/6.0 = 1.30 percent, which from Table 7-9 of the SPM indicates between 10- to 22-percent damage to the cover layer. There is an 18-percent probability that a 50-year surge event will occur in a 10-year interval. Therefore, the damage caused by this event was not considered in the maintenance of the groins. A factor of 20-percent damage to the armor layer every 10 years was used to determine the cost of groin maintenance.